CLNS 00/1697
CLEO 00-21

Bounds on the CP Asymmetry in $b \to s\gamma$ Decays

CLEO Collaboration

(January 2, 2001)

Abstract

We have measured the CP asymmetry $\mathcal{A}_{CP} \equiv (\Gamma(b \to s\gamma) - \Gamma(\bar{b} \to \bar{s}\gamma))/(\Gamma(b \to s\gamma) + \Gamma(\bar{b} \to \bar{s}\gamma))$ to be $\mathcal{A}_{CP} = (-0.079 \pm 0.108 \pm 0.022)(1.0 \pm 0.030)$, implying that, at 90% confidence level, $\mathcal{A}_{CP}$ lies between –0.27 and +0.10. These limits rule out some extreme non-Standard-Model predictions, but are consistent with most, as well as with the Standard Model.

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Direct CP violation can lead to a difference between the rates for $b \to s\gamma$ and $\bar{b} \to \bar{s}\gamma$, giving rise to a non-zero value for the CP asymmetry

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(b \to s\gamma) - \Gamma(\bar{b} \to \bar{s}\gamma)}{\Gamma(b \to s\gamma) + \Gamma(\bar{b} \to \bar{s}\gamma)} \quad .$$

Such an asymmetry occurs only if the decay is due to two or more amplitudes with differing strong phases and differing weak phases. The Standard Model (SM) predicts [1] that this asymmetry is very small, less than 1%. Recent theoretical work [1,2] suggests that non-SM physics may contribute significantly to a CP asymmetry, giving asymmetries perhaps as large as 10 – 40%. The advantage of an inclusive measurement, in contrast to an exclusive measurement, *e.g.* $B \to K^*(890)\gamma$ [3], is that the strong phase is calculable. In this Letter, we describe a measurement of a CP asymmetry in $B \to X_s\gamma$, a close approximation to $\mathcal{A}_{CP}$ as defined above, with a small admixture from $b \to d\gamma$. We rule out very large asymmetry values.

The data used in this analysis were taken with the CLEO detector at the Cornell Electron Storage Ring (CESR), a symmetric e^+e^- collider. They consist of 9.1 fb^{-1} on the $\Upsilon(4S)$ resonance, and 4.4 fb^{-1} at a center-of-mass energy $\sim$ 60 MeV below the resonance. The on-resonance sample contains 10 million $B\bar{B}$ events and 30 million continuum events, while the off-resonance sample contains 15 million continuum events.

The CLEO detector [4] measures charged particles over 95% of 4π steradians with a system of cylindrical drift chambers. (For 2/3 of the data used here, the innermost tracking chamber was a 3-layer silicon vertex detector.) Its barrel and endcap CsI electromagnetic calorimeters cover 98% of 4π. The energy resolution for photons near 2.5 GeV in the central angular region, $|\cos\theta_\gamma| < 0.7$, is 2%. Charged particles are identified by specific ionization measurements (dE/dX) in the outermost drift chamber, and by time-of-flight counters (ToF) placed just beyond the tracking volume. Muons are identified by their ability to penetrate the iron return yoke of the magnet.

The signature for $b \to s\gamma$ is a photon with energy sufficiently high that it is unlikely to come from other B decay processes. We take our photon energy range as 2.2 – 2.7 GeV. With this requirement, there is little background from other B decay processes. There is substantial background from continuum processes, and so continuum suppression is a key ingredient in this analysis, as it is in any $b \to s\gamma$ analysis. The other ingredient needed for an asymmetry measurement is flavor tagging. Not needed for an asymmetry measurement, unlike absolute rate measurements of $b \to s\gamma$, is a good knowledge of the efficiency, since it cancels when the ratio is taken.

We use two different methods of flavor tagging. In the first, we accept events with a high energy photon and a high momentum lepton. The lepton charge tags the flavor of the 'other' B, tagging the flavor of $b \to s\gamma$ correctly 89% of the time. $B^0 - \bar{B}^0$ mixing is the dominant reason for mistags. The second method of flavor tagging is 'pseudoreconstruction', described below and used in our previous $b \to s\gamma$ analysis [5]. Here, we are directly tagging the flavor of the $b \to s\gamma$ decay, so mixing does not cause mistags. With aggressive use of particle identification, we have achieved a correct flavor identification rate of better than 90%.

We use Monte Carlo simulation (along with the measured value for $B^0 - \bar{B}^0$ mixing) to determine the performance of our flavor identification methods. For this, we describe

the $b \to s\gamma$ process with a spectator model [6], and vary the spectator model parameters to determine systematic errors to flavor identification from the modelling of the $b \to s\gamma$ process.

Pseudoreconstruction was originally introduced as a continuum background suppression technique. Requiring a high momentum lepton also suppresses the continuum, particularly when use is made of the angle between lepton and photon. So, our flavor-tagging methods are also part of our continuum suppression.

We select hadronic events having normalized Fox-Wolfram [7] second moment R_2 less than 0.45, and containing a photon with energy between 2.2 and 2.7 GeV, in the "good barrel" region of the calorimeter ($|\cos\theta_\gamma| < 0.7$). The high energy photon must not form a π^0 or η with any other photon in the event.

Part of our continuum suppression comes from eight carefully chosen event shape variables: R_2, $S_\perp$ (a measure of the momentum transverse to the photon direction [8]), R_2' (the value of R_2 in the primed frame, the rest frame of e^+e^- following an assumed initial state radiation of the high energy photon, with R_2 evaluated excluding the photon), $\cos\theta'$ (θ' the angle, in the primed frame, between the photon and the thrust axis of the rest of the event), and the energies in 20° and 30° cones, parallel and antiparallel to the high energy photon direction. While no individual variable has strong discrimination power, each posesses some. Consequently, we combine the eight variables into a single variable r that tends towards $+1$ for $b \to s\gamma$ events and tends towards –1 for continuum background events, using a neural network [8]. Distributions in the neural net variable r, for Monte Carlo samples of $b \to s\gamma$ signal and continuum background, and off resonance data, are shown in ref. [5].

While the background to $b \to s\gamma$ from other B decay processes is small, it is not negligible. We investigated it with a $B\bar{B}$ Monte Carlo sample that included contributions from $b \to u$ and $b \to sg$ processes, as well as the dominant $b \to c$ decay. We found that the overwhelming source of background ($\sim$90%) is photons from π^0 or η decay. Consequently we tuned the Monte Carlo to match the data in π^0 and η yields.

For the lepton tagging method of flavor identification, we require a high momentum lepton ($1.4 < P < 2.2$ GeV/c), either a muon (identified by passing through at least 5 interaction lengths of material) or an electron (identified by E/P, track-cluster matching, dE/dX, and shower shape). The distribution in cosine of angle between lepton and high energy photon, $\cos\theta_{\ell-\gamma}$, is isotropic for $b \to s\gamma$ signal events, and strongly back-to-back peaked for continuum background events. We make loose cuts on r and $\cos\theta_{\ell-\gamma}$, and then define weights w_i in the 2D $r - \cos\theta_{\ell-\gamma}$ space, where $w_i = s_i/[s_i + (1+a)b_i]$, s_i is the expected signal yield in the i-th bin, b_i is the expected continuum background yield in that bin, and a is the luminosity scale factor between on-resonance and off-resonance data samples (≈ 2.0). Weights so defined minimize the statistical error on the $b \to s\gamma$ yields. Expected yields are obtained from Monte Carlo simulation. Should the Monte Carlo simulation of signal or background be flawed, the weights will not be optimum, but they will not lead to incorrect results. We sum weights on and off resonance, and subtract the off-resonance sum, scaled by $\mathcal{L}/E_{cm}^2$, from the on-resonance sum (the On-Off subtraction). We also subtract the background from B decay processes. We do this separately for events tagged with an ℓ^- and events tagged with an ℓ^+, and compute the raw asymmetry, obtaining $\mathcal{A}_{lep}^{raw} = 0.148 \pm 0.141$. Summed weights, and the number of events with non-zero weight, are given in Table I.

This raw asymmetry must be corrected for the mistag fraction α, by dividing it by $1-2\alpha$. Mistags come mainly from $B^0 - \bar{B}^0$ mixing, a contribution to α of $\chi_d/2$, which we take from

	N	$W(b)$	$W(\bar{b})$
On	507	127.10 ± 8.90	107.34 ± 7.81
Off	135	24.96 ± 3.25	23.24 ± 3.37
Sca	279.9	51.73 ± 6.76	48.08 ± 6.97
$B\bar{B}$	39.8	12.80	12.80
Sub	187.3	62.57 ± 11.18	46.46 ± 10.47

TABLE I. Yields (weights) for b-flavored ($W(b)$), and $\bar{b}$-flavored ($W(\bar{b})$), for On, Off, Scaled Off, $B\bar{B}$ background, and On – Scaled Off – $B\bar{B}$ background. The number of events passing all cuts, N, is also given. Lepton tag analysis.

CLEO's dilepton mixing measurement [9], $\chi_d = 0.157$. (By using CLEO's dilepton mixing measurement, we eliminate some systematic errors, in particular the uncertainty in the ratio of B^+B^- to $B^0\bar{B}^0$ events.) Other sources include secondary decays $b \to c \to s\ell\nu$, leptons from J/ψ decays, and hadrons misidentified as leptons. These we determine, from Monte Carlo studies, to be 0.033. Adding this to the mixing contribution gives $\alpha = 0.112 \pm 0.013$. The corrected value of asymmetry is

$$\mathcal{A}_{lepton\ tag} = +0.191 \pm 0.181 \quad .$$

For events not containing high momentum leptons, we use the pseudoreconstruction method of flavor identification. We search those events for combinations of particles that reconstruct to a $B \to X_s\gamma$ decay. For X_s we use a $K_S^0 \to \pi^+\pi^-$ or a charged track consistent with a $K^\pm$; and 1 – 4 pions, of which at most one may be a π^0. We calculate the candidate B momentum P, energy E, and beam-constrained mass $M \equiv \sqrt{E_{beam}^2 - P^2}$. A reconstruction is deemed acceptable if it has $\chi_B^2 < 20$, where

$$\chi_B^2 \equiv \left(\frac{E - E_{beam}}{\sigma_E}\right)^2 + \left(\frac{M - M_B}{\sigma_M}\right)^2 \quad .$$

(Typically, $\sigma_E \approx 46$ MeV, $\sigma_M \approx 3.5$ MeV.) If an event contains more than one acceptable reconstruction, the "best" is selected on the basis of an overall χ^2 consisting of χ_B^2 plus contributions from particle identification.

We discriminate between signal and background using χ_B^2, r (from the shape variables), and $|\cos\theta_{tt}|$, where θ_{tt} is the angle between the thrust axis of the candidate B and the thrust axis of the rest of the event. These three variables are combined into a single variable r_c, that tends towards $+1$ for signal and -1 for continuum background, using a neural net. As for the lepton tag analysis, we count weights, not events, with weights defined as earlier, now a function of r_c. Weights are summed for events tagged as b-flavored, $\bar{b}$-flavored, and ambiguous, separately on and off resonance, and an On-Off resonance subtraction is performed.

Note that with pseudoreconstruction the flavor can be correctly or incorrectly tagged (if it reconstructs to a charged B, or to a neutral B decaying to $K^\pm$), or it can be tagged as ambiguous (if it reconstructs to a neutral B decaying to K_S^0). A major source of incorrect

tags is using a $\pi^\pm$ for a $K^\pm$. To reduce this source of incorrect tags, we have been aggressive in our $K^\pm$ identification.

For runs for which the ToF measurement was available and reliable, 3/4 of the luminosity, we used both ToF and dE/dX for $K^\pm$ and $\pi^\pm$ identification; for the other 1/4 of the luminosity, we used only dE/dX. The cut when both ToF and dE/dX were used was a $\Delta\chi^2$ cut, the difference between the χ^2 of the ToF plus dE/dX fits assuming $K^\pm$ and assuming $\pi^\pm$. Whether or not ToF was used, we used a 3σ cut (or the 2D equivalent) for $\pi^\pm$ identification. For $K^\pm$, if the $K-\pi$ separation was very good ($> 6\sigma$), or if it was hopeless ($\sim 0\sigma$), we used a 3σ cut or the equivalent. In between, we cut more harshly, in a manner that depended on the computed $K-\pi$ separation. We achieved a misidentification probability of 8.5% when ToF and dE/dX were used, 12.2% when only dE/dX was used.

Because the pseudoreconstruction analysis has three possible outcomes – b-flavored, $\bar{b}$-flavored, ambiguous – the formulation is more complex than the lepton tag case. Let α be the probability that a taggable event be incorrectly tagged, β be the probability that a taggable event be declared ambiguous, and γ be the probability that an event which is actually ambiguous be tagged as b or $\bar{b}$. For the analysis using ToF and dE/dX, we use Monte Carlo to obtain $\alpha = 0.085 \pm 0.006$, $\beta = 0.016 \pm 0.004$, $\gamma = 0.40 \pm 0.05$, while for the analysis with dE/dX only, we obtain $\alpha = 0.122 \pm 0.007$, $\beta = 0.013 \pm 0.005$, $\gamma = 0.49 \pm 0.06$.

Using α, β, γ, we compute a raw asymmetry

$$\mathcal{A}^{raw}_{pseudo} = \frac{N(b) - N(\bar{b})}{N(b) + N(\bar{b}) - (\gamma/(1-\gamma))N(ambig)} \ ,$$

and then correct by a factor $(1 - \beta/(1-\gamma))/(1 - 2\alpha - \beta)$. This factor is more complicated than $1 - 2\alpha$, but is essentially equivalent to it. We combine the corrected asymmetries for runs with ToF and dE/dX and runs with dE/dX only, weighting each by the expected statistical accuracy. We find

$$\mathcal{A}_{pseudo} = -0.178 \pm 0.132 \ \ .$$

Summed weights, and the number of events with non-zero weight, are given in Table II.

Pseudoreconstruction and lepton tag results are consistent with each other, and are statistically independent. We combine them, weighting each by the expected statistical accuracy, giving

$$\mathcal{A}_{comb} = -0.072 \pm 0.107 \ \ .$$

The increased statistical power from using weights, as compared to counting all events with non-zero weights, was 1.6 for the lepton tag analysis and 4.0 for the pseudoreconstruction analysis.

False asymmetries in the lepton tag analysis would be caused by a difference in detection plus identification efficiency for electrons *vs.* positrons, or μ^- *vs.* μ^+. By measuring the rates for ℓ^- and ℓ^+ from On-Off subtracted data, we find such false asymmetries to be consistent with zero, and safely bounded by ± 0.01, which we take as the additive systematic error for the lepton tag analysis.

False asymmetries in the pseudoreconstruction analysis would be caused by particle identification biases favoring $K^\pm$ over $K^\mp$, or favoring $\pi^\pm$ over $\pi^\mp$. By measuring the momentum spectra (On-Off subtracted) for candidate K^-, K^+, π^-, and π^+, noting the biases in particle

	N	$W(b)$	$W(\bar{b})$	$W(?)$
On	5542	171.17 ± 6.81	174.73 ± 6.97	22.97 ± 2.72
Off	2318	52.80 ± 3.11	48.37 ± 2.88	5.49 ± 0.96
Sca	4877.8	111.55 ± 6.56	101.50 ± 6.06	11.50 ± 2.02
$B\bar{B}$	113.2	8.67	8.67	1.20
Sub	551.0	56.95 ± 9.46	64.56 ± 9.23	10.27 ± 3.39
On	2408	65.49 ± 3.81	72.34 ± 4.26	8.21 ± 1.34
Off	1062	24.18 ± 2.13	20.63 ± 1.85	2.69 ± 0.70
Sca	2113.7	47.52 ± 4.19	40.70 ± 3.68	5.53 ± 1.44
$B\bar{B}$	34.6	2.93	2.93	0.41
Sub	259.7	15.03 ± 5.67	28.71 ± 5.63	2.27 ± 1.97

TABLE II. Yields (weights) for b-flavored ($W(b)$), $\bar{b}$-flavored ($W(\bar{b})$), and ambiguous ($W(?)$), for On, Off, Scaled Off, $B\bar{B}$ background, and On – Scaled Off – $B\bar{B}$ background. The number of events passing all cuts, N, is also given. The upper half of the table is the pseudoreconstruction analysis with ToF and dE/dX; the lower half is with dE/dx only.

identification that these spectra could accommodate, and translating that into a limit on false asymmetry, we established that an additive systematic error of ±0.01 adequately covers the uncertainty from particle identification.

False asymmetries in the pseudoreconstruction analysis would also be caused by particle detection biases, in particular from the different interaction cross sections for K^+ and K^-. There is about 1 g/cm^2 of material between the interaction point and the back of the tracking volume. This, with the known K^+ and K^- cross sections, limits that source of false asymmetry to ±0.007.

If either $B \to \pi^0 X$ or $B \to \eta X$ had a nonzero CP asymmetry, then that would creep into the measured $b \to s\gamma$ asymmetry through the feeddowns $\pi^0 \to \gamma$ and $\eta \to \gamma$. In making the subtraction for $B\bar{B}$ background, we have so far assumed these asymmetries are zero (as expected theoretically), apportioning the background equally between b and $\bar{b}$. In addition, we have measured the π^0 and η asymmetries, treating each as if it were the high energy photon, and following the same method as for measuring the $b \to s\gamma$ asymmetry. Combining the lepton tag and pseudoreconstruction analyses, we find a π^0 asymmetry of +0.070 ± 0.056, an η asymmetry of +0.156 ± 0.333, both consistent with zero. Allowing for the fact that the lepton tag and pseudoreconstruction asymmetries may be different, we find corrections to the lepton tag analysis of +0.034 ± 0.025, to the pseudoreconstruction analysis of –0.024 ± 0.017, and to the combined analysis of –0.007 ± 0.014.

Multiplicative systematic errors result from uncertainties in the mistag rate, uncertainties in the scale factor for the off-resonance subtraction (resulting from change in event shape with the 60 MeV E_{cm} shift), and uncertainties in the subtraction for other B decay processes. For the lepton tag analysis, we estimate ±3.4% from the mistag uncertainty, ±1.1% from the Off-resonance subtraction uncertainty, ±4.0% from the $B\bar{B}$ subtraction uncertainty, ±5.4% total. For the pseudoreconstruction analysis, we estimate ±1.6% from the mistag

uncertainty, $\pm 1.9\%$ from the Off-resonance subtraction uncertainty, $\pm 2.6\%$ from the $B\bar{B}$ subtraction uncertainty, $\pm 3.6\%$ total. The combined multiplicative systematic error, lepton tag plus pseudoreconstruction, is $\pm 3.0\%$.

We have verified that the analysis proceedure, when applied to Monte Carlo samples with actual CP asymmetry, correctly finds the CP asymmetry introduced, whether large, small, or zero.

The asymmetry we have measured is a weighted sum over a variety of $b \to s\gamma$ decays – charged B, neutral B; low mass X_s, high mass X_s; *etc.* In particular, those $b \to s\gamma$ decays that are inherently ambiguous under a pseudoreconstruction analysis, *i.e.*, neutral B decays to neutral kaons, have asymmetries measured only by the lepton tag analysis. If the different varieties of $b \to s\gamma$ decays have asymmetries that differ among themselves by no more than ± 0.10, then the unevenness in our weightings will lead to an asymmetry that differs from the asymmetry with uniform weightings by no more than ± 0.02. We have looked for dependence of $\mathcal{A}_{CP}$ on M_{X_s} or E_γ, and within our limited statistics found none.

Also included in the asymmetry we have measured is a component from $b \to d\gamma$. Within the framework of the Standard Model, the rate for $b \to d\gamma$ decays is down by a factor of $|V_{td}/V_{ts}|^2 \approx 1/20$, but the asymmetry is up by the reciprocal of the same factor, *i.e.* 20, and of opposite sign. The ratios of efficiencies for $b \to d\gamma : b \to s\gamma$ are 1.1 for the lepton tag analysis and 0.56 for pseudoreconstruction; 0.65 combined. While the misidentification parameter α for the lepton tag analysis is essentially the same for $b \to d\gamma$ as it is for $b \to s\gamma$, for the pseudoreconstruction analysis, α for $b \to d\gamma$ is very poor, ≈ 0.4, only slightly better than a random guess ($\alpha = 0.5$). Thus, with the weightings that we have given to the lepton tag and pseudoreconstruction analyses, and assuming a ratio of branching fractions for $b \to d\gamma$ to $b \to s\gamma$ of 1/20, we have measured a weighted sum of CP asymmetries $\mathcal{A} = 0.965\mathcal{A}(b \to s\gamma) + 0.02\mathcal{A}(b \to d\gamma)$.

In conclusion, we have measured a CP asymmetry in $b \to s\gamma$ plus $b \to d\gamma$ decays. Our final result is

$$\mathcal{A}_{CP} = (-0.079 \pm 0.108 \pm 0.022)(1.0 \pm 0.030) \quad .$$

The first (and by far the largest) error is statistical; the second is additive systematic and includes an allowance of ± 0.020 for the non-uniform weightings over the various $b \to s\gamma$ decay modes; the third is multiplicative systematic.

This measurement implies that, at 90% confidence level, $\mathcal{A}_{CP}$ lies between the limits

$$-0.27 < \mathcal{A} < +0.10 \quad .$$

These limits rule out some extreme non-Standard-Model predictions, but are consistent with most, as well as with the Standard Model. Note that the analysis reported here uses the same data sample as CLEO's measurement [3] of the CP asymmetry in the exclusive decay $B \to K^*(892)\gamma$, and so is not statistically independent of it.

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This work was supported by the National Science Foundation, the U.S. Department of Energy, the Research Corporation, the Natural Sciences and Engineering Research Council of Canada, the Swiss National Science Foundation, the Texas Advanced Research Program, and the Alexander von Humboldt Stiftung.

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